Final Technical Report for Office of Naval Research grant N00014-03-1-0583

June 2008

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I. Summary

The emphasis of the research summarized here concerns the production of enhancements in the scattering of high frequency sound by various penetrable cylinders. Examples of such cylinders in water include solid polymer (plastic) cylinders having flat or curved ends, plastic cylindrical shells containing a liquid having a low speed of sound, and a solid fiberglass cylinder. In some cases the cylinders were encased in stainless steel or fiberglass. In most cases studied the enhancements are associated with waves transmitted through the material within the cylinder and reflected off of the curved back wall of the cylinder. Various imaging methods are demonstrated including bistatic synthetic aperture sonar (SAS) and supersonic acoustic holography. The holographic and SAS images clearly indicate that contrary to an opinion held by some researchers, it is possible to have image features associated with waves transmitted within the objects being viewed which are much brighter than image features associated with external specular reflection or edge diffraction by the object. Some related research is described concerning the scattering by a partially exposed cylinder and the theory for a sphere centered on an acoustic Bessel beam.

II. Introduction, Research Tasks, and Personnel

ONR Grant N00014-03-1-0583 "Novel High Frequency Signatures for Classification/Identification" pertained to research carried out at Washington State University related to approaches to acoustic methods for classification and identification being studied also at NSWC-PCD. This grant supported or partially supported a sequence of investigations which were summarized in reports by the P.I. (Marston) in the ONR Report CDs issued annually for FFY 2004-2007 [1-4]. While the P.I. was involved in all aspects of the investigation, the graduate students supported tended to give their attention

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
18-06-2008

2. REPORT TYPE
Final Technical

3. DATES COVERED *(From - To)*
February 2003 - March 2008

4. TITLE AND SUBTITLE
Novel High Frequency Signatures for Classification / Identification

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N000140310583

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Marston, Philip L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Physics and Astronomy Department
Washington State University
Pullman, WA 99164-2814

8. PERFORMING ORGANIZATION REPORT NUMBER
N00014-03-1-0583-FR

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
ONR 32
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release: Distribution unlimited

13. SUPPLEMENTARY NOTES
Email address: marston@wsu.edu Telephone Number: 509-335-5343

14. ABSTRACT
The emphasis of the research summarized here concerns the production of enhancements in the scattering of high frequency sound by various penetrable cylinders. Examples of such cylinders in water include solid polymer (plastic) cylinders having flat or curved ends, plastic cylindrical shells containing a liquid having a low speed of sound, and a solid fiberglass cylinder. In some cases the cylinders were encased in stainless steel or fiberglass. In most cases studied the enhancements are associated with waves transmitted through the material within the cylinder and reflected off of the curved back wall of the cylinder. Various imaging methods are demonstrated including bistatic synthetic aperture sonar (SAS) and supersonic acoustic holography. The holographic and SAS images clearly indicate that contrary to an opinion held by some researchers, it is possible to have image features associated with waves transmitted within the objects being viewed which are much brighter than image features associated with external specular reflection or edge diffraction by the object. Some related research is described concerning the scattering by a partially exposed cylinder.

15. SUBJECT TERMS
Acoustical Scattering, Cylinders, Bistatic Synthetic Aperture Sonar, Supersonic Acoustic Holography, Caustics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	19	19b. TELEPONE NUMBER *(Include area code)*

to specific projects related to the grant objectives. Consequently listing those students and their projects serves to introduce some of the tasks. In some cases support for a particular student was shared with other ONR grants with a corresponding splitting of tasks. In addition separate remarks will be noted for senior personnel partially supported by this grant.

A. Graduate Students:

1. *J. Stevick* was partially supported during the initial grant year. He assisted in improving and testing the scattering facility and did scattering experiments of a preliminary nature.

2. *K. Baik* was partially supported by this grant mostly during the first grant year. By agreements with ONR program staff (C. Loeffler) Baik emphasized the measurement of backscattering by a partially exposed cylindrical target as a function of target exposure and frequency. The target was lowered through a free surface in a tank of water and the backscattering was measured. By agreement with the ONR SWAMSI program manager at that time (N. Chotiros), Baik's activities were transitioned to the SWAMSI grant. Eventually he succeeded in developing a Kirchhoff approximation for the scattering which is described in his Ph.D. thesis and in a paper that has been accepted for publication [5, 6]. He also worked out the detailed timing of certain ray contributions. This result has turned out to be helpful in identifying SAS image features in pond experiments carried out at NSWC-PCD by UW-APL researchers in March 2008. While Baik was supported by this grant his experiments emphasized scattering features that would be present even for a rigid target. He also confirmed that some elastic features in the backscattering by tilted steel cylindrical shells (studied previously in Marston's group for empty and water-filled shells [7-9]) are also present in the backscattering when the shell is filled by a dense polymer. The implications are that the damping of surface guided waves introduced by the contact with the polymer is not sufficient to suppress some strong scattering features. Eventually (when he was supported by the ONR SWAMSI program) Baik's research emphasized bistatic SAS and acoustic holography for various cylindrical targets.

3. *Aubrey Espana* was supported in part by this grant. She began a series of investigations of backscattering signatures associated with rays transmitted through various kinds of polymer cylinders. She also assisted with some initial experiments carried out using fiberglass targets and she also carried out experiments in light scattering for situations where the rays were closely analogous to those present in the acoustic scattering. While she initially studied scattering by bluntly truncated polymer cylinders where the backscattering enhancements had been previously noted by Blonigen and Marston [10], the primary emphasis of her research was on a situation where the end of the cylinder was curved. This change produced a caustic having different properties than the caustic previously studied. This was done because certain types of cylindrical mines appear to have hemispherical ends. During Aubrey's involvement with this grant there was an interest at NSWC-PCD in the development of codes for calculating scattering amplitudes based on the refraction and internal reflection of rays within cylindrical targets. Aubrey's measurements were supplied to researchers at NWSC-PCD associated with contact N0001405WX20465 for purpose of the testing of such codes at NSWC. Aubrey was transitioned to research supported by ONR grant N000140610045 on the

scattering of evanescent waves by various targets. That work has involved plastic as well as metallic targets.

4. *Chris Dudley* began his affiliation with this grant by working on the modernization of the experimental facilities in several ways that will not be described in detail here. That modernization was supported also by grants N000140310585 and N000140410075 with the result that in addition to improvements in the acquisition of time-domain backscattering data as a function of tilt angle, it has been possible to acquire data showing spectral features ("acoustic color") as a function of target tilt angle as well as bistatic data. The bistatic data was subsequently used for producing SAS images and acoustic holograms of the scattering. These experiments were done on scaled targets in our 12-foot diameter water tank. The division of effort is correlated with the source of support as follows: (1) backscattering and bistatic imaging of scattering by targets where internally refracted rays are dominant: (the grant discussed here and the related follow-on grant N000140810024); (2) backscattering and high-frequency acoustic color of aluminum and other metallic cylinders and acoustic color associated with guided-wave features (ONR SWAMSI grant N000140410075); (3) low-frequency acoustic color for the identification of resources to be studied with evanescent wave excitation (grant N000140610045). Dudley's emphasis was on category (1) measurements and involved a variety of cylindrical targets fabricated from polymers and fiberglass. In some cases the targets were solid cylinders and in other cases they consisted of shells filled with a liquid having a low speed of sound. This liquid consisted of a mixture of HFE-7500 and silicone-oil having a density of 1.03 gm/cm^3 and a sound velocity 881 m/s. The properties were selected to display a range of features expected for penetrable targets. In April 2008, Dudley completed his Ph.D. thesis [11] with the support of this grant and the follow-on grant (N000140810024). An abstract and summary chapter from his thesis are given in Sections III and IV of this report..

5. *Jon LaFollett* began scattering research supported in part by this grant in May 2007. His research is supported also in part by the SWAMSI grant. During the March 2007 NSWC-PCD / UW-APL pond experiments on the SAS imaging of a 1-foot diameter x 5-foot long aluminum cylinder, it became evident that features present in monostatic SAS images were associated with elastic guided-wave elastic features of the target as well as with the proximity with the interface. As a consequence of the manpower intensive nature of such experiments it seemed appropriate to assign Jon the task of laboratory based tests to verify the existence of some of the brightest of those scattering features and the task of developing ray-based models. What makes Jon's work different than Baik's work on imaging is that Baik emphasized free field bistatic imaging while Jon has emphasized monostatic SAS imaging and the consequence of proximity to a flat interface. With the joint support of the follow-on grant and the SWAMSI grant, Jon was able to participate on-site in the interpretation of NSWC-PCD pond experiments in March 2008.

B. Senior Personnel:

Miscellaneous tasks carried out primarily by senior personnel and supported in part by this grant. The senior personnel include the P.I. (Marston) and Assistant Research Professor David Thiessen. Marston's efforts in addition to advising the aforementioned research included a series of related theoretical investigations. A partial list is given as follows:

(a) During the first year of the grant, Marston found that it was possible for the case of a circular cylinder breaking through a flat surface to put the Kirchhoff approximation for the backscattering in a simple analytical form [12]. That form involved only Bessel functions but only a special case was considered: the case of normal incidence, which corresponds to symmetric illumination of the cylinder. That result had been previously expressed by Gaunaurd by using Struve functions [13]. The advantage of Marston's formulation is that it may be generalized away from the special case of 90° grazing angle originally considered by Marston to the case of an arbitrary grazing angle. That generalization was carried out by Baik and is documented in his Ph.D. thesis and in his publication [5, 6].

(b) In an effort to understand the effect of the internal contents of a metal shell on the damping of generalized elastic Lamb waves guided by the shell, early in the grant effort Marston carried out a calculation of the radiation damping of the guided elastic wave for the following special case: the system of a steel plate bonded to a polymer half-space with no-slip bonding circulations. The results of the analysis indicate that the radiation damping introduced by the polymer was often less than the damping for the simpler case of a plate in contrast with a water half-space. The implications are that (provided a suitable frequency is used) the backscattering enhancements for truncated shells documented by Morse and Marston [7, 8] could also likely be present if the shell is filled with a polymer material.

(c) Do mixed-mode internal reflections in circular cylinders produce an Airy caustic? Early in the grant Marston examined this issue since a simple Airy caustic (which is analogous to a rainbow) gives a bright feature in the bisatic scattering. It is well known from elementary optics that such caustics exist for a circular or spherical object when the effective acoustical refractive index exceeds unity, which means that the speed of the wave in the interior is less than that of the surroundings. That is usually the case for shear waves in a plastic (a solid polymer) immersed in water. It is also the case for refracted and reflected waves within liquid filled thin shells when the sound speed in the liquid is small (such as the aforementioned HFE-7500-silicone oil mixture). Consequently circular cylinders exhibit simple Airy caustics as was verified by Dudley in the case of a liquid filled cylindrical shell. For solid objects, however, it is also possible to have mixed-mode echoes in which some of the rays are shear waves which mode convert upon reflection to longitudinal waves. In the case of a typical polymer plastic object in water the effective acoustical refractive index of the shear wave is $n_S > 1$ and that for the longitudinal wave is $n_L < 1$. For most plastics the longitudinal wave speed exceeds the speed of sound in water. Consequently it is of interest to determine if an Airy caustic is produced when one (or more) internal shear ray(s) is (are) followed by one (or more) internal longitudinal ray(s). The needed equations to describe the relation between the scattering angle θ_S and the impact parameter b (which describes the deviation from normal incidence) are derived by Williams and Marston [14]. A farfield Airy caustic corresponds to the condition where the following derivative vanishes: $d\theta_S/db = 0$. Marston carried out a search for roots of that type where $n_S = c_W/c_S$ was selected to exceed unity in the range of typical polymers or cylinder contents of interest and $n_L = c_W/c_L$ was less than unity. Here c_W is the speed of sound in water. It was found that for all cases examined that when there was at least one chord (or internal ray) of the longitudinal type, there were no Airy

caustics in the scattering no matter how many chords or internal rays of the shear type. Consequently it appears that for most practical situations mixed-mode Airy caustics do not exist for a cylinder illuminated at normal incidence or for a sphere.

(d) Caustic conditions for tilted cylinders having curved ends: Various generalizations of the prior analytical results of Blonigen and Marston [10] were worked out by Marston. Strong far-field caustics can be produced associated with internal reflections from the end of such a cylinder and the existence of those caustics was verified in the aforementioned experiments carried out by Aubrey Espana.

(e) Scattering of a Bessel beam by a sphere: Exact analytical solutions to the scattering of objects by beams of sound are virtually unknown. With the partial support of this grant Marston worked out an analytical solution [15] for the special case of a sphere centered on a Bessel beam where the sphere could be any type of isotropic sphere: rigid, soft, solid, shell, etc. In each case the sphere is centered on the Bessel beam. As an initial test of this result various high frequency limiting cases were worked out and were found to be in agreement with the partial wave series. In addition various solid sphere and shell cases were computed and were interpolated using ray theory. It was determined that it was possible to completely suppress a resonance by appropriate selection of beam parameters [16].

(f) Thiessen performed several engineering tasks pertaining to the design of the improved tank facility. He also carried out an investigation of the properties of some of the liquids that were used (or were considered for use) in experiments with liquid filled targets. He also has occasionally advised and directed students when the P.I. was not immediately available.

(g) Thiessen set up and has maintained our facilities for carrying out finite elements based scattering calculations using the COMSOL code. He has assisted students in such calculations and in some cases carried out specialized models designed to lend insight in student projects. In addition he has succeeded in reproducing Marston's analytical results for scattering of an acoustic Bessel beam by a sphere by using finite elements [17]. This served not only to confirm the analytical formulation but also to provide confidence in COMSOL based FEM calculations.

III. Christopher Dudley's Ph.D. Thesis: Title and Abstract

Christopher Dudley "High Frequency Material Issues in Scattering of Sound by Objects in Water," (Ph. D. Thesis, Materials Science Program, Washington State University, Pullman, WA, May 2008)

Abstract:

Ray theoretic models were shown to predict scattering enhancements from laboratory scale cylindrical targets in water. Synthetic aperture sonar and acoustical holographic images were constructed from bistatic scattering. Targets of increasing complexity from material properties were investigated. Models range from simple ray optic style to corrections for transversely isotropic materials. To correctly model the complexity of anisotropic material such as fiberglass, the five independent elastic constants and the density were measured. In all of the cylindrical shells and solid targets, enhancements are observable for k*a* values ranging from 9 to 40 where k is the wavenumber and *a* is the cylinder radius.

The simpler targets consist of a low sound speed fluid within a thin plastic or fiberglass shell ($11 < ka < 40$). Shells were taken to be sufficiently thin so that the shell dynamics could be neglected in the models. The fluid has a density near that of water with a sound speed less than water. It is straightforward to construct the location and length of bright features for the fluid filled shells.

Solid finite cylinders of polystyrene ($9 < ka < 23$) and fiberglass ($ka = 17$ and 22) were found to have more structure in echoes than the fluid filled shells. Bright image features existed from longitudinal as well as shear wave propagation within the polystyrene. A model including shear and longitudinal wave components showed good agreement with experiments with respect to timing and length of features for Rexolite®. Fiberglass is the most complex due to the anisotropic symmetry of the material. The slowness matrix allowed for modeling of timing aspects of the solid fiberglass cylinder.

For a flat polystyrene half-space there is predicted to be a prominent enhancement of the acoustic reflection for an angle of incidence near 40°. Measurements showed the existence of a related peak in the reflection from solid polystyrene Rexolite cylinders with ka near 9. Related peaks in the reflection from coated cylinders were observed.

The properties of sound transmitted by a stainless steel plate in water was investigated. The relevant S_2^b leaky Lamb waves have been previously demonstrated on spherical shells [Kaduchak et al., J. Acoust. Soc. Am. 96, 3704 (1994)]. Directional properties of guided waves excited on a stainless steel plate in water were observed. Guided waves could be excited on the plate having group and phase velocities oppositely directed and such waves could profoundly influence the transmission of sound.

IV. Christopher Dudley's Ph.D. Thesis: Summary Chapter and Discussion

Note: The following section (with minor modifications) reproduces the Summary chapter of Dudley's thesis. The chapter numbers refer to specific thesis chapters. Chapter 1, which is not summarized, is an introductory chapter that also discusses some aspects of the apparatus.

This thesis considers several aspects of how acoustic rays which are able to travel within a target in water and be internally reflected can have a large effects on the scattering of sound by the target. The material within the target is taken to be homogeneous and it is assumed that there is only weak absorption of sound in the frequency range of the observations. For the materials used in this experiment the ability to observe the scattering features associated with a wide variety of rays indicates that this assumption may not be applicable in practical situations for some objects of interest for shear as well as longitudinal waves within the cylinder. Consequently in the case of plastic cylinders it is especially important to identify scattering features associated with longitudinal as well as shear transmitted waves.

Chapter 2 concerns scattering experiments performed with thin-walled cylinders made of fiberglass with the inside filled with a liquid mixture having a speed of sound of 881 m/s which is significantly less than the speed of sound in water. Aspects of these experiments are like a cylindrical version of the well-known focusing spheres often used for the calibration of sonar systems. The first aspect of these experiments concerned the evolution of the backscattering response to a short tone burst as the tilt angle of the cylinder relative to the illumination was varied from 0° (broad side) to 90° (end-on) illumination. The use of illumination by short tone bursts made it possible to

discriminate between various mechanisms which produced backscattering echoes. The experiments were carried out for a wavenumber radius product ka in the range 16-24. The experiments displayed a strong enhancement of the backscattering in the region associated with a critical tilt angle where the outgoing acoustic wavefront becomes doubly flat. This corresponds to the caustic-merging transition (CMT) previously investigated by Blonigen and Marston [10] for the case of a tilted polystyrene cylinder having flat ends. There was also evidence of CMT contributions from additional ray bounces however in all cases the strength of the CMT scattering enhancement appeared to become less noticeable when the time burst frequency was increased above 400kHz. That may be because of irregular distortion of wavefronts associated with the transmission of sound through the fiberglass wall.

Chapter 2, in the next part, examines a more elementary type of caustic scattering enhancement observed in bistatic scattering when the cylinder was illuminated at zero tilt (corresponding to broadside illumination). The enhancement was the acoustic manifestation of an Airy caustic associated with an internal ray having 2 chords and is directly analogous to the enhancement that causes a rainbow in the refraction of light with water drops. The use of short tone bursts made it possible to distinguish between rays reflected from the outside of the cylinder which were significantly weaker than the focused rainbow rays reflected from within the cylinder. As expected the rainbow enhancement was especially strong within a narrow range of scattering angles displaced from exact backscattering. This data was supplied to NSWC Panama city Florida for the purpose of testing the development of certain scattering codes.

Chapter 3 concerns the monostatic and bistatic scattering properties of thin walled cylindrical shells filled with the same low-speed liquid used in Chapter 2. In this chapter, however, the walls of the cylinder were more homogeneous, being made of a commercially available thin-walled plastic cylindrical shell composed of Tenite. The monostatic experiments displayed many of the features visible in the tilted cylinder experiments described in Chapter 2. The excitation in this case was generalized to include a short wide-bandwidth pulse centered on 208 kHz as well as a short tone bursts. Both experiments displayed the CMT enhancement. In addition, the tone burst experiment displayed a significant amount of reverberation in the case of end-on illumination (a tilt angle of 90°). This reverberation was associated with longitudinal waves transmitted down the axis of the liquid-filled cylinder and reflected from the flat ends of the cylinder.

Chapter 3, in the next and perhaps most important part, concerns the collection and application of bistatic data for which a receiver hydrophone was scanned along a horizontal line. While that data was useful for displaying the evaluation of the scattering as a function of scattering angle when the cylinder was illuminated with different tilt angles, perhaps the most significant application use of phase as well as magnitude information in the bistatic scattering to contstruct two types of images. One type of image was bistatic synthetic aperture sonar that facilitates the display of the apparent locations of scattering centers associated with the set of scattered waves leaving the target region. The other type of image was a form of bistatic acoustic holography in which only the supersonic components of the wavenumber of the scattering by the target was used in the analysis. In the case of the liquid-filled thin-walled circular shells studied in Chapter 3 with both types of images for certain ranges of tilt angles the brightest feature in the

image was associated with a two-chord internal reflection that causes a relatively flat outgoing scattered wavefront. This feature on the images was often significantly brighter than the external specular reflection from the wall of the cylinder. To gain a better understanding of the features that contribute to that strong bistatic enhancement, the bistatic scattering amplitude from that feature was measured for a range of tilt angles and the ratio of the strength of that feature to the strength of the specular reflection was plotted as a function of tilt angle. This ratio displayed a pronounced minimum near 14 degrees of tilt in agreement with a detailed analysis of the relative phase of the associated paths contributing to the outgoing wavefront. Near that tilt the relative phase was predicted to be 180° (or π radians) causing a destructive interference.

Chapter 4 concerns monostatic and bistatic scattering experiments with flat ended plastic cylinders made of Rexolite (a form of polystyrene) and ordinary polystyrene. The monostatic scattering displayed a pronounced CMT enhancement similar to the one studied by Marston and Blonigen [10]. The emphasis of this chapter was on the consequences of internally reflected shear and longitudinal rays on the appearance of bistatic SAS and holographic images produced as described in Chapter 3. Noticeable bright features in the images were visible from longitudinal as well as shear waves reflected from within the cylinder. Bright features associated with the CMT enhancement of the shear internal reflection were distinctly visible. In addition some bright image features from longitudinal (as well as shear waves) were visible from waves transmitted through the flat ends of a tilted cylinder. Finally experiments were carried out to analyze the internal reverberation from a cylinder illuminated at near end-on incidence (a tilt angle of 90°).

Chapter 5 concerns the scattering properties and related image features for the case of a solid fiberglass circular cylinder made of a common form of structural fiberglass commonly known as e-glass. This was selected for investigation because this type of cylinder displays what is perhaps the simplest form of elastic anisotropy: the material is transversely isotropic with the symmetry axis corresponding to the cylinder's axis. Fiberglass is used on some objects of interest however, the consequences of material anisotropy on the scattering from objects in water has been largely unexplored. In addition, most software currently available for scattering calculations based on the method of finite elements generally does not include the consequences of material anisotropy. Consequently it is important to study the scattering in this relatively simple case because, the existence of specific features reported here for the first time could serve as a benchmark for testing future computational algorithms.

Chapter 5 begins with an investigation of the bistatic scattering and holographic and SAS imaging in the simplest geometry which is the case of a vertically aligned cylinder illuminated by a horizontally propagating acoustic wave in the form of a short pulse. In addition to specular reflection from the cylinder, both the holographic and SAS images reveal a strong contribution suggestive of rays transmitted through the cylinder and internally reflected from the back wall of the cylinder.

Chapter 5 emphasizes the case of a tilted horizontal fiberglass cylinder illuminated by a horizontally propagating acoustic pulse. The backscattering is displayed as a function of tilt angle. That plot reveals several prominent features that show that waves propagating on or within the fiberglass can have a substantial influence on the backscattering. One of the strong backscattering features was associated with a wave on

the fiberglass which was a generalization of a leaky Rayleigh wave on a flat fiberglass surface. For the enhancement observed the generalized Rayleigh wave propagates across the flat end of the cylinder. The theory for the Rayleigh velocity in this case is based on prior theoretical results for surface waves on anisotropic media in the absence of fluid loading. The observed face crossing backscattering enhancement is a generalization of one previously described for isotropic solid metallic cylinders by Gipson and Marston [18]. In addition there is a considerable amount of delayed energy leaving the fiberglass cylinder visible in the backscattering. This is suggestive of a significant amount of internally reflected waves within the fiberglass.

Chapter 5 includes a detailed discussion of bistatic holographic and SAS images for the case of a tilted horizontal cylinder where the tilt angle was selected to lie in a range where the delayed image features associated with waves transmitted through the cylinder were especially bright. Some of these features were identified by an analysis of quasi-transverse wave generated in the meridional plane of the tilted cylinder and reflected from the backside of the cylinder. The analysis of the timing of this image contribution requires an understanding of the distinction between the energy flow direction and the wave vector direction for the refracted quasi-transverse wave. The analysis is able to give the observed difference in timing between the external specular reflection and the internally reflected quasi-transverse wave which propagates within the tilted cylinder. In addition the observed spatial length of the bright feature is described by the model. There is also a very bright delayed additional image feature not described by this analysis. The cause of that feature, other than its association with some elastic response of the fiberglass, was left unresolved.

Chapter 6 concerns the reflection of high-frequency sound from the outside of horizontal circular plastic cylinders and the way the reflectance depends on the tilt angle of the cylinder relative to the illumination. The research in that chapter was motivated by a theoretical prediction for the simple case of a polymer half-space in contact with water. The dependence of the reflection coefficient on the angle of incidence for the case of typical solid polymers (which have shear wave velocities less than the speed of sound in water) have more prominent features than in the more commonly studied case of metals such as steel or aluminum. In the case of a plastic the reflection coefficient has a prominent peak associated with the critical angle for launching an internally refracted longitudinal wave parallel to the interface. The calculated peak causes a substantial increase in the reflectivity that, in the case of polystyrene or Rexolite in water, is predicted to occur when the angle of incidence is close to 40°. At a sufficiently high frequency it is to be expected that the reflection by a tilted cylinder would display a similar peak when the tilt angle of the cylinder relative to the illumination is close to 40°. Observation of such a peak, however, requires bistatic measurements with a scattering in the region near $180° - 2 \times 40° = 100°$. The emphasis of this chapter concerns measurements pertaining to the existence of such a peak in the acoustic amplitude reflectance for tilted cylinders illuminated by a pulse with observations near k*a* of 9 where k is the wavenumber and *a* is the cylinder radius. The observations with a Rexolite cylinder show a maximum near the predicted tilt angle however the maximum is not as sharply peaked (and is lower in amplitude) than the prediction for a flat surface. In addition evidence is given that the maximum is also present when the plastic is coated by a thin fiberglass or stainless steel layer. This phenomena may be relevant to the

reflection of sound by explosive filled cylinders in water since many explosives have shear and longitudinal wave properties similar to fiberglass.

Chapter 7 concerns the transmission of sound through flat stainless steel plates in water. It is also concerned with the directional properties of guided waves excited on the plate. It was previously demonstrated by Kaduchak, Hughes, and Marston [19] that guided waves could be excited on a steel shell in water having group and phase velocities oppositely directed and that such waves could profoundly influence the scattering. These waves are often described as waves with a negative group velocity. There seems to be no prior investigation on the importance of such waves on the transmission of acoustic beams through steel plates or shells in water. In the present investigation it was demonstrated that for excitation at an appropriate frequency, the spatial properties of the transmitted sound had directional features expected for the case of the radiation by a leaky wave on the plate having a negative group velocity. This observation may be helpful for the interpretation of the transmission of high frequency sound through the walls of elastic shells.

Appendices are included which discuss some geometric issues that are needed for the interpretation of scattering measurements in several of the chapters. In addition some of the properties of the materials investigated are tabulated. Some aspects are described of the apparatus constructed for scattering the hydrophone needed for the bistatic scattering measurements and the holographic and SAS imaging. Some aspects of computer codes developed are documented.

V. Baik's Publication on the Kirchhoff Approximation: Title and Abstract

Kyungmin Baik and Philip L. Marston, "Kirchhoff approximation for a cylinder breaking through a plane surface and the measured scattering," IEEE Journal of Oceanic Engineering (accepted for publication).

Abstract: When considering the application of quantitative ray theory to the backscattering of sound at grazing incidence by a circular cylinder partially buried in sediment, the analysis is complicated by a transition in the number of reflected rays. For broadside insonification the number of rays geometrically backscattered may be 0, 1, 2, or 3 depending on the exposure of the cylinder. A formulation for the scattering based on the Kirchhoff approximation is given which avoids discontinuities associated with transitions in the number of rays. The formulation is tested for the experimentally simpler case of a steel cylinder hung through a free surface with a 30 degree grazing angle relative to the air-water interface. Tone burst insonification was used with a wave number radius product ka from 9.6 to 16. The measured dependence of the backscattering on exposure is similar to predictions except for extra features present for a slightly exposed cylinder. The approximation is also supported by comparison with an exact theory for backscattering by a half-exposed rigid cylinder in a flat pressure-release surface. Predictions for the dependence on exposure are also shown for the case of a cylinder emerging from a flat rigid surface.

VI. Marston's Publications on Bessel Beam Scattering by Spheres

(a) Philip L. Marston, "Scattering of a Bessel beam by a sphere," J. Acoust. Soc. Am. 121, 753-758 (2007).

Abstract: The exact scattering by a sphere centered on a Bessel beam is expressed as a partial wave series involving the scattering angle relative to the beam axis and the conical angle of the wave vector components of the Bessel beam. The sphere is assumed to have isotropic material properties so that the nth partial wave amplitude for plane wave scattering is proportional to a known partial-wave coefficient. The scattered partial waves in the Bessel beam case are also proportional to the same partial-wave coefficient but now the weighting factor depends on the properties of the Bessel beam. When the wavenumber-radius product k*a* is large, for rigid or soft spheres the scattering is peaked in the backward and forward directions along the beam axis as well as in the direction of the conical angle. These properties are geometrically explained and some symmetry properties are noted. The formulation is also suitable for elastic and fluid spheres. A partial wave expansion of the Bessel beam is noted.

(b) Philip L. Marston, "Acoustic beam scattering and excitation of sphere resonance: Bessel beam example," J. Acoust. Soc. Am. 122, 247 (2007)

Abstract: The exact partial wave series for the scattering by a sphere centered on an ideal Bessel beam was recently given by Marston ["Scattering of a Bessel beam by a sphere," J. Acoust. Soc. Am. 121, 753–758 (2007)]. That series is applied here to solid elastic spheres in water and to an empty spherical shell in water. The examples are selected to illustrate the effect of varying the beam's conical angle so as to modify the coupling to specific resonances in the response of each type of sphere considered. The backscattering may be reduced or increased depending on properties of the resonance and of the specular contribution. Changing the conical angle is equivalent to changing the beam width. Some applications of the Van de Hulst localization principle to the interpretation of the partial wave series and to the interpretation of the scattering dependence on the beam's conical angle are discussed. Some potential applications to the analysis of the scattering by spheres of more general axisymmetric beams are noted.

VII. Selected Research Results

Various results were documented in the aforementioned dissertations [5, 11], publications [6, 15, 16], related minor publications [20-22], and reports [1-4]. Some selected results are shown here. The emphasis here is on items that have not been widely distributed.

(a) High Frequency Backscattering by a Polymer Cylinder Having Hemispherical Ends: The result summarized here is from Aubrey Espana's experiments and was summarized in the 2005 Annual Report [2]. The backscattering was measured as a function of tilt angle where zero tilt corresponds to broadside illumination. A cylinder with hemispherical ends was fabricated from a polystyrene-based material. Acoustic backscattering was measured as a function of tilt angle using tone bursts. The tilt angle is the deviation from broadside illumination. **Figure 1** shows the backscattering (log scale with 53 dB dynamic range) as a function of tilt angle (vertical axis) and time (horizontal axis). In this example k*a* is 27 where k is the acoustic wavenumber and *a* is the radius of the cylinder. From the tilt dependence and the evolution of the time and amplitude of the signature, scattering contributions associated with a caustic found in an analogous light-scattering experiment [2] is also evident in the acoustic scattering. The red patch slightly left of the center of the figure is associated with the caustic enhancement. That signal is

generally an order-of-magnitude larger in amplitude than the specular reflection off the front hemispherical end of the cylinder (visible on the left). Since the cusp angle of the caustic depends on the tilt angle, it is to be expected that acoustic bistatic scattering could be used to determine the contents of a cylinder having a curved end or (in the case previously studied [10]) a flat end.

(b) Scattering by a Liquid-Filled Fiberglass Cylindrical Shell Having Flat Ends: The result summarized here is from Chapter 2 of Dudley's Thesis [11]. (For a summary of that Chapter see Section IV of this report.) Dudley fabricated a fiberglass cylindrical shell which had flat ends except that the end closest to the source had a removable plug to facilitate filling the shell with a liquid. The cylinder was filled with a liquid whose sound speed (881 m/s) was much less than that of the surrounding water. The density (1.03 gm/cm^3) was nearly the same as that of water. The relative acoustical refractive index of the internal liquid is 1.68. The cylinder was excited with a 7-cycle tone burst and backscattering was recorded as the cylinder was rotated from broadside to end-on over a range that exceeded 90°. This was done at 300 kHz, 400 kHz and 450 kHz bursts. Since the cylinder was approximately 2.6 cm in diameter the k*a* (wavenumber-radius product) values were 16, 21, and 24. The result shown in **Figure 2** is for k*a* = 16 though the features for the other values of k*a* are similar. Various ray features are identified from the arrival time and from the feature evolution with tilt angle. The bright feature for a tilt angle of 40° corresponds to the caustic merging transition (CMT) previously discussed by Blonigen and Marston [10] for a polystyrene cylinder. Experiments of this type confirmed the existence of a sequence of such CMT features an even number of internal chords when the effective refractive index (which depends on the tilt angle of the cylinder) is equal to the number of internal chords. In case of a CMT at 40° tilt this corresponds to 2 internal chords. For 4 and 6 internal chords the CMT shifts to 70° and 77° respectively. Those features are also visible in **Figure 2** but at delayed times.

(c) Bright SAS and Acoustic Hologram Features in the Scattering by a Flat-Ended Solid Polymer Cylinder: Chapter 4 of Dudley's thesis [11] discussed experiments on targets of this type. **Figures 3 and 4** are examples from the same set of bistatic measurements for the case of a Rexolite cylinder. (Rexolite is a stable form of polystyrene known to have reproducible acoustic properties.) In **Figure 4** the data was processed using supersonic acoustic holography and was processed and displayed using a method discussed by Dudley [11] and by Baik [5]. On these images Dudley has computed the predicted positions of certain features calculated from ray theory. In both images these features were calculated relative to a specified location shown by the superposed small black circle corresponds to an edge echo on the lower right. In both cases the lowest white dashed line is the external specular reflection with a slope and length calculated from ray theory. In **Figure 4 (a)** two later white dashed lines are shown which are calculated from ray theory for shear waves within the polymer that have been reflected internally off of the cylinder's back side once (for the earlier of the 2 lines) and twice (for the later of the 2 lines). In **Figure 4 (b)**, a tilted black line is shown that is calculated from theory for the case of a longitudinal wave that is reflected once off of the back side of the cylinder. These different lines serve to identify the cause of the associated bright image features. The presence of a bright feature in the case of a longitudinal wave within the polymer indicates that bright elastic features are likely to be visible even when the attenuation of

shear waves turns out to be large for the sonar system used. **Figure 3** is the corresponding bistatic SAS image computed for the same data set. The method of processing closely resembles one developed by S. G. Kargl at UW-APL for the processing of SAX-04 and NSWC-PCD pond data. The physical location of the cylinder is shown on the image. Comparison of Figures 3 and 4 facilitates the identification of the cause of various bright SAS features. Dudley found that enclosing a polystyrene cylinder in a thin fiberglass shell or a thin stainless steel shell did not completely suppress some of the aforementioned image features (Chapter 6 of his thesis). Dudley also found related bright image features in the bistatic scattering for tilted liquid-filled thin polymer shells and solid cylinders made of fiberglass (known as e-glass) in which the fibers run parallel to the axis of the cylinder. In both cases the locations of some of the image features on the hologram could be predicted using ray theory. See respectively Chapters 3 and 5 of his thesis.

(d) Data Archive: Various data sets for the backscattering and bistatic measurements described in Dudley's thesis have been archived in computers maintained in Marston's research group. For information contact Philip Marston. Some of the data has been supplied to NSWC-PCD staff and used in testing codes [23].

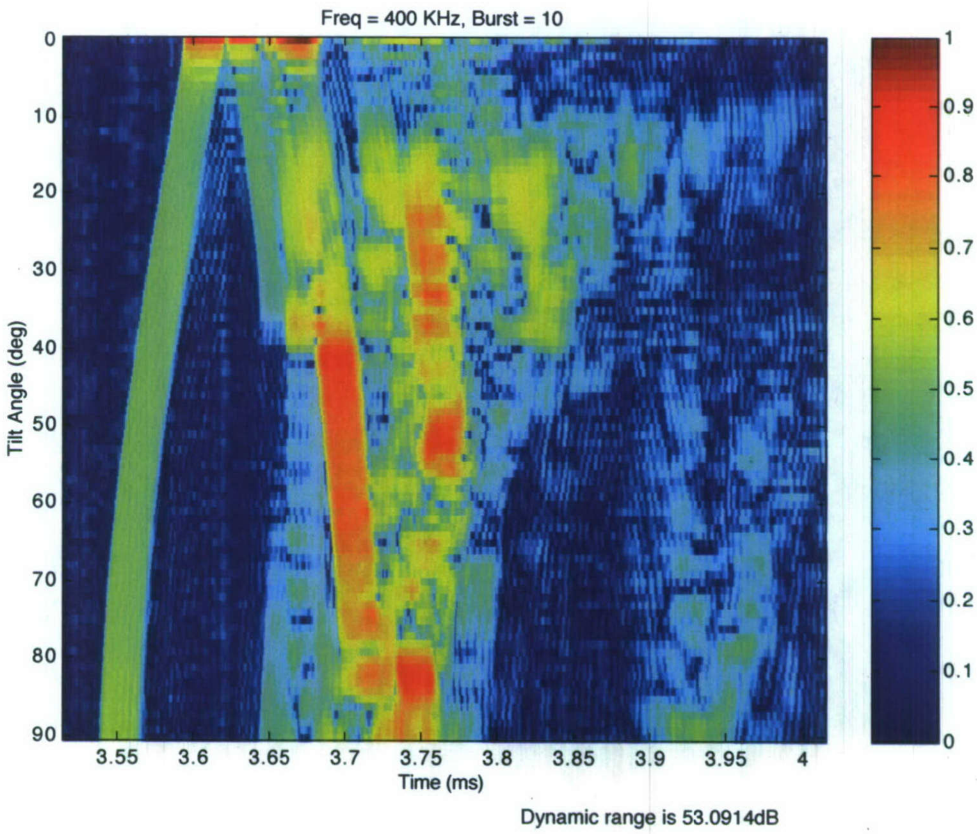

Figure 1. Measured backscattering amplitude (as indicated by the color scale on the right), for a plastic cylinder with hemispherical ends as a function of tilt angle (the vertical axis) and time (the horizontal axis). The incident wave is a 10-cycle tone burst. The dark red region in the upper left is the specular reflection with broadside

illumination. The broad enhancement from 40-70 degrees, visible to the left of center, is a scattering contribution associated with waves transmitted through the plastic. This contribution is enhanced as a result of one of the caustics caused by the curved end of the cylinder. There is a second caustic near 85 degrees. The dark blue level (indicated as level zero on the scale on the right) indicates the signal is at least 53 dB below the strongest echo.

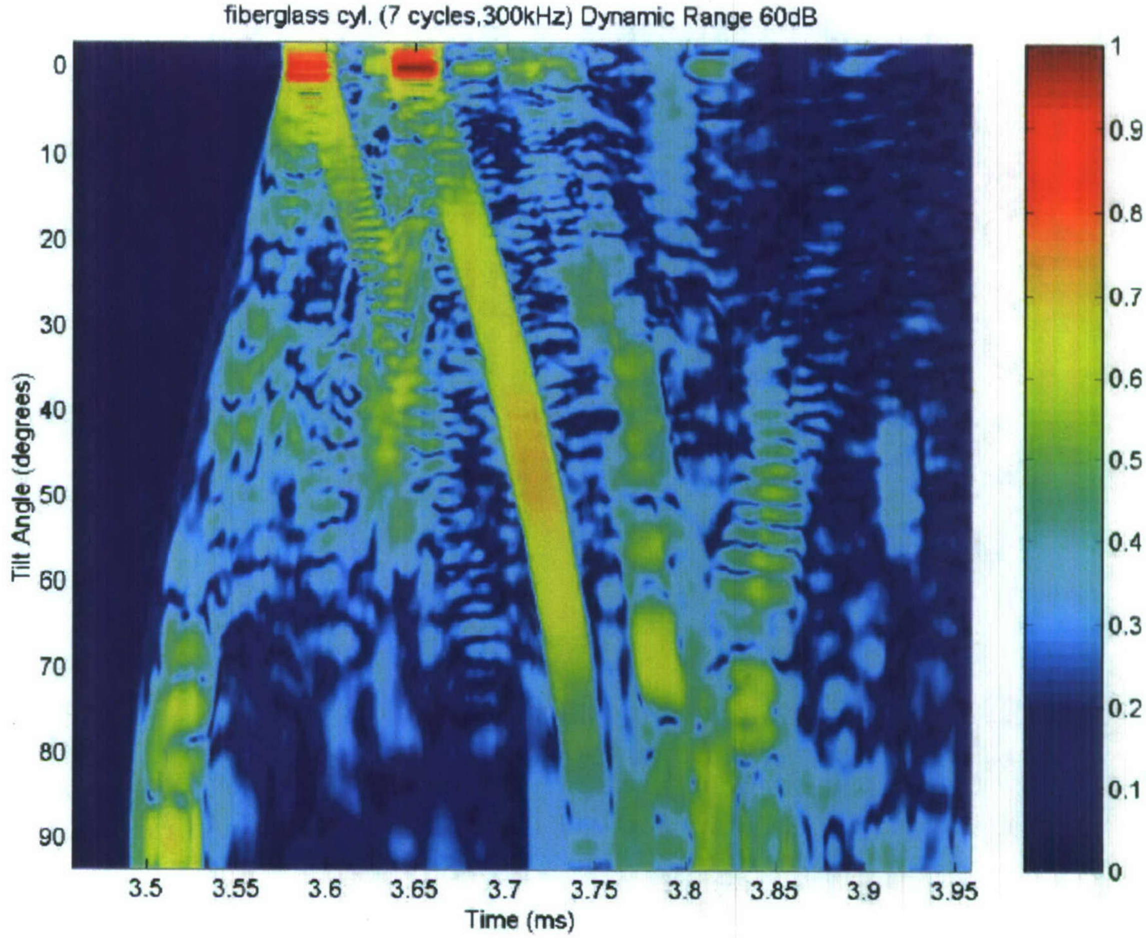

Figure 2. Measured backscattering amplitude (as indicated by the color scale on the right), for a liquid-filled fiberglass cylindrical shell with flat ends plotted as a function of tilt angle (the vertical axis) and time (the horizontal axis). The relative acoustical refractive index of the internal liquid is 1.68. The incident wave is a 7-cycle tone burst and the wavenumber-radius product is 16. The red region in the upper left is the specular reflection with broadside illumination. The adjacent dark red region to the right is the partially focussed reflection from the far-side of the shell. The broad enhancement from 30-75 degrees, visible to the left of center, is a caustic merging backscattering enhancement. The dark blue level on the left (indicated as level zero on the scale on the right) indicates the signal is at least 60 dB below the strongest echo.

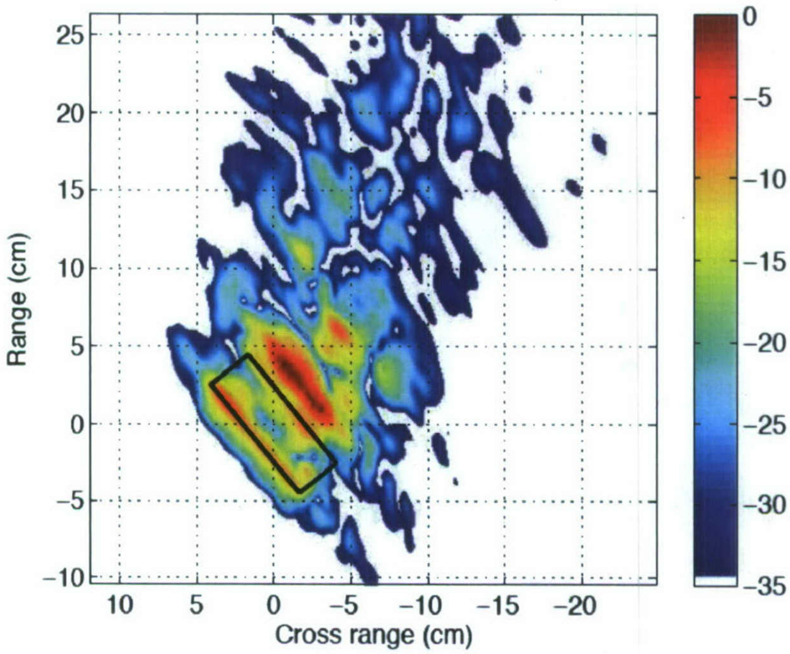

Figure 3. Bistatic SAS image of a tilted polystyrene Rexolite cylinder with the tilt angle set at 24° relative to broadside illumination. An outline of the cylinder location is superposed on the image in black. The bright feature off-set to the upper right of the cylinder is caused by the focused internal reflection from the back side of the cylinder. It is brighter than the external reflection visible on the lower left. The corresponding hologram is shown in Figure 4. From Dudley's Ph. D. thesis [11].

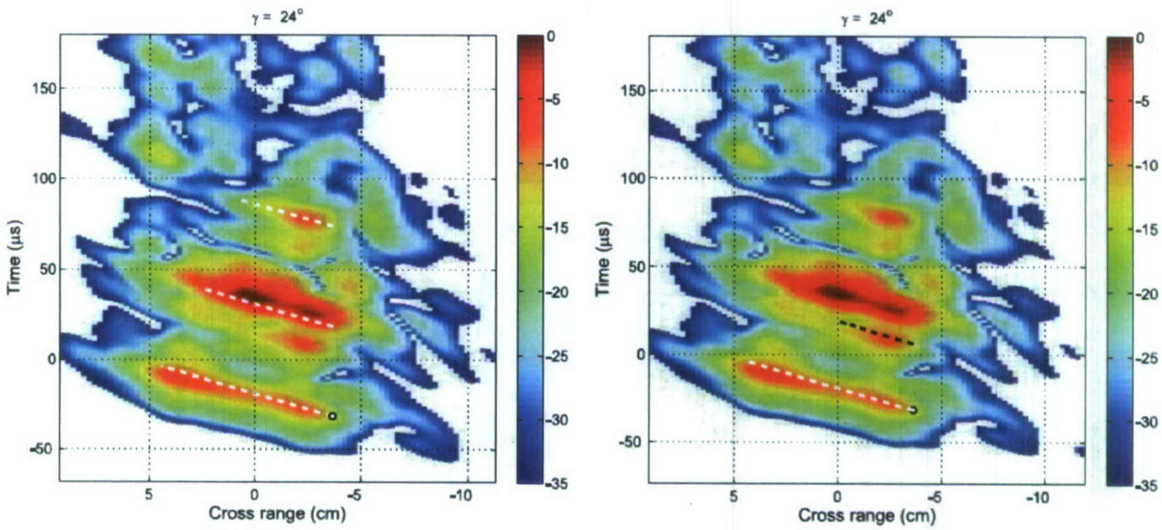

Figure 4. Bistatic acoustic hologram of a tilted Rexolite cylinder from the same data used in Fig, 3. superimposed with ray theory predictions. (a) Predicted locations of the external specular reflection (white dash with dot) and the internal shear wave reflections (white dash). (b) Predicted locations of the external specular reflection (white dash with dot) and back-side longitudinal reflection (black dash). The vertical axis is time and the amplitude is indicated by the color scale on the right. From Dudley's Ph. D. thesis [11].

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